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Solar cooker realizations in actual use: An overview

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A B S T R A C T

Presently fossil sources still dominate the domestic sector, which is the largest primary energy-consuming sector across the globe. Energy for cooking is considered to be the most important end use in the sector, and its demand is continuously increasing [11]. Cooking with solar energy is one of the promising solutions for meeting energy demands. However, its large-scale dissemination and popularization still remain limited. A number of solar energy-based cooking technologies exist all over the world, but a very few are actually in use. Major work on this subject is intended for research purposes only.

This paper deals with the recent advances in developments and the performance analysis of a solar cooker's technologies. The meticulous review on such technologies provides an overview on existing solar cookers developed during the past two decades, especially major geometry components that affect their performances such as the booster mirror, absorber tray, insulation, glazing system, cooking vessel, and thermal energy storage materials. The thermal performance parameters, such as figures of merit and cooking power used for testing and evaluating the performance of solar cooking, energy and exergy analysis, have also been addressed. The performance of both single- and double-axis tracking mechanisms applied in the cooker structure is also discussed. Attempt has also been made to summarize the CO_2 mitigation potential through such devices.

Contents

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Nomenclature

F_1	first figure of merit (m²K/W)
F_2	second figure of merit (dimensionless)
P_s	standard cooking power (W)
P	cooking power (W)
τ_{boil}	standard boiling time (min m²/kg)
η	energy efficiency of the solar cooker (%)
ψ	exergy efficiency of the solar cooker (%)
E_o	energy output of the solar cooker (W)
E_i	energy input of the solar cooker (W)
E_{xo}	exergy output of the solar cooker (W)
E_{xi}	exergy input of the solar cooker (W)
IG	insulation on a horizontal surface at stagnation (W/m²)
$\overline{IG}$	average solar radiation on horizontal surfaces (W/m²)
Δt	time interval (s)
T_{wi}	initial temperature of water (K)
T_{wf}	final temperature of water (K)
ΔT_w	temperature difference of water (K)
T_{ps}	maximum absorber plate temperature (K)
T_{as}	ambient air temperature at stagnation (K)
$\overline{T}_a$	average ambient air temperature (K)
T_{ra}	reference ambient temperature (K)
T_s	surface temperature of the sun (K)
A_c	absorber plat area (m²)
A_{sc}	intercept area of solar cooker (m²)
M	mass of water (kg)
C	heat capacity of water (J/kg k)
F′	heat exchange efficiency factor (dimensionless)
η_o	optical efficiency (dimensionless)
C_R	heat capacity ratio (dimensionless)

1. Introduction

The greatest amount of energy consumed worldwide comes from fossil fuels. Energy consumption in developed countries is growing at a rate of approximately 1% per year, and at a rate of 5% per year in developing countries [1,2]. The global energy demand is expected to increase, and fossil fuels are not projected to compensate that growing demand, mainly because of the decline in world oil production and environmental issues (i.e., atmospheric pollution, greenhouse effect and global warming). Due to increasing cost of fossil-fuel cost, renewable energy technologies have received remarkable attention at the international level over the last few years. Renewable sources play important role in sustainable development and they are environmentally friendly energy sources [2]. Among the renewable energy sources, solar energy is considered the most abundant and a viable option for thermal energy applications. As Thirugnanasambandam et al. [3] highlighted, the total annual solar radiation falling on the earth is more than 7500 times of the world's total annual primary energy consumption. The annual solar radiations are reaching on the earth's surface, approximately 3.4×10^6 EJ, is an order of magnitude greater than all the estimated non-renewable energy resources, including fossil fuels and nuclear.

When considering thermal applications of solar energy, solar cooking presents the best option and the most promising appliance for solar thermal energy [4]. Solar cookers provide many advantages, including fuel economy, reduction in greenhouse gas emission, firewood utilization saving, lower cost and high durability, among others [4]. However, in many parts of the world, especially in developing countries wood and fossil fuel-based cooking energy resources still predominate with the highest share of global energy consumption in the residential sector. This situation creates serious ecological problems, such as deforestation [5]; economical and health problems are also consequences of firewood use. On the other hand, the global demand for cooking energy is expected to increase with the increasing human population over in the upcoming years.

Currently, renewable energy sources supply about 14% of the total world energy demand, and their potential will play an important role in the world's future [10,11]. The share of solar thermal applications is likely to grow, especially to meet domestic energy requirements. Thus, solar energy is a promising option, and having capability to becoming a leading energy source for cooking [11–13]. Actually, Solar cooking International claims that solar cooking has been or is being introduced in 107 countries [6].

Solar cooking technology began with the invention of the first solar box cooker by a French–Swiss physicist named Horace de Saussure; his work was introduced in 1767 [6]. In 1945, Sri M.K. Ghosh constructed the first commercial box-type solar cooker [7,8]. In 1961; the United Nations Conference on New Sources of Energy included many authorities on solar cooking technology was held [8]. During 1976; Arizona in the United States, Barbara Kerr and Sherry Cole developed box solar cookers that are easy to construct and use. The first U.S. solar cookbook, Solar Cooking Naturally, was written by M.H. Gurley Larson, in 1983 [6]. Since the 1950s, Indian scientists have also been interested in solar cookers; as an option for avoiding deforestation, they have designed and commercialized a number of solar ovens. Actually, India operates several programs to promote solar energy as a cooking fuel in rural areas and, to an extent; they have been successful [9]. Today's solar cooker technologies demonstrate a considerable development in terms of design and performance parameter.

The development of solar cooking systems in the near future will also help to resolve the existing problems with the technology like long duration cooking, uncontrolled temperatures, tracking strategies, and thermal storage techniques, etc. and thereby, overcome the barriers to the dissemination of the solar cookers. Many opportunities exist to promote the future potential of solar cookers, so more research attempts must be carried out to increase their efficiency and thus enhance their current performance.

In this paper, recent advances in research and development of solar cooking technology are presented. Thermal performance, energetic and exergetic analysis, and new understanding throughout the world are analyzed. Solar cooker systems equipped with tracking devices are discussed. Mitigation potential of carbon dioxide using solar cookers is also presented.

2. Solar cookers: principle and types

A solar cooker converts solar energy into heat, which is used to cook food kept in the cooking utensil. Solar cookers also enable some significant processes such as pasteurization and sterilization [8]. Different types of solar cookers have been designed and developed around the world in the past and are still being improved by scientists and researchers. Therefore, the classification of solar cookers is a complicated task. In the present review, solar cookers are classified into three main categories based on the type of collector and temperature order: box-type cookers, concentrating-type cookers and non-focusing type cookers. Within these three, main categories are included cookers with direct or indirect heat-transferring modes, cookers with or without storage, and cookers with tracking or non-tracking systems.

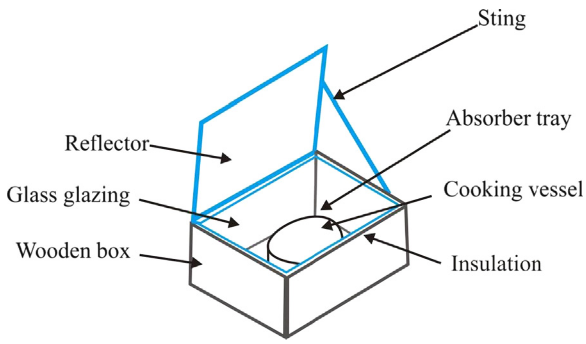

Fig. 1. Components of a box solar cooker.

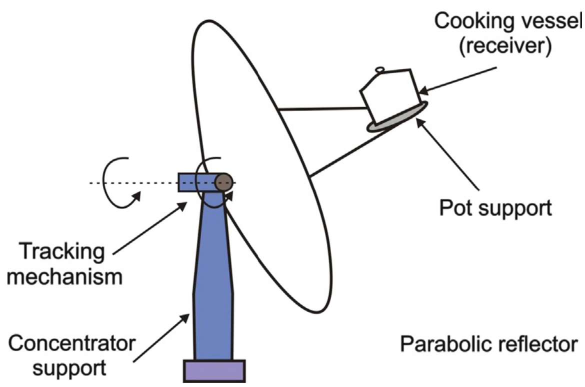

Fig. 2. Components of a parabolic solar cooker.

Direct-type solar cookers use solar radiation directly in the cooking process, while the indirect cookers use a heat transfer fluid to transfer the heat from the collector to the cooking unit [14]. The thermal energy storage option must be provided with solar cookers in order to allow late evening/night cooking and overcome the limitations of solar cookers during off-sunshine hours. Sometimes, these cookers are equipped with one- or two-axis tracking systems to follow the sun.

A solar box cooker consists of an insulated box with a transparent glass cover. The box is usually equipped with reflective surfaces (booster mirrors) to reflect sunlight into the box [6]. A description of solar box cooker is shown in Fig. 1. In order to increase sunlight absorption, the inner part (absorber) of the box is painted black. It often accommodates more than one pot, and up to four cooking vessels filled with food can be placed inside the box loaded with food [15,16]. With this type of cooker, a temperature of around 100 °C can be achieved, which makes it possible to cook the food by boiling.

Many researchers and manufacturers around the world are interested by developing box solar cookers. Hence, different designs and prototypes were recognized, especially in the years 1990s and early 2000s [17–25]. As underlined by Erdem Cuce and Pinar Mert Cuce in their comprehensive review, each component of the box cooker has a significant influence on cooking power [8]. For example, booster mirrors can provide a great deal of solar radiation intensities, which enhances the efficiency of the box solar cooker and reduces the cooking time. Therefore, some researchers became highly intrigued by this important element and performed several research study and analyses [26–30]. An absorber tray (plate) painted black with high absorptivity must be chosen to improve the performance of a solar box cooker. This subject has attracted investigations from the beginning, until now [31–36]. For the energy efficient box solar cooker output, heat loss from inside the box to the outer environment should be minimized. Therefore, transparent insulation materials for the insulation of glazing are greatly recommended by several researchers [37–39]. The glazing is another component that is also important for maximizing the energy output of the solar box cooker [40–42]. Other researchers carried out a great deal of research and investigations concerning cooking vessel and focused on his geometry; they found that cylindrical and rectangular-shaped cooking vessels made of aluminum or copper and coated black on their outsides are generally good for box cookers [43–48].

Concentrating-type cookers utilize multifaceted mirrors, Fresnel lens, parabolic or spherical collectors to attain higher temperatures [49] that are suitable for all types of food cooking. These cookers are typically designed with a one- or two-axis tracking system allowing for the following of the course of the sun. Concentrating-type cookers exhibit a high degree of reflector clearness for a maximum optical reflection and minimum possible heat losses in the receiver. The best-known design in this category is the point focusing paraboloid solar cooker (Fig. 2). It consists simply of a parabolic reflector with a cooking pot that is located on the focus point of the cooker and a stand to support the cooking system [8]. Concentrating-type cookers attracted more attention, and several conceptual ideas are becoming reality around the world. We cite, for example, the portable solar cooker of Arenas [50], the conical solar cooker of Sharaf [51], the Fresnel-type domestic SPRERI concentrating cooker of Sonune and Philip [52], the multiple-use communal solar cooker of Franco et al. [53] and the three solar concentrating-type cookers for domestic direct use of Patel and Philip [54].

The category of non-focusing type cookers includes flat-plate and vacuum-tube type cookers, these cookers using heat transfer fluid to carry thermal energy. They have the advantage of being suitable for indoor cooking applications, but are more expensive to produce than the other types [49]. One of the such cookers realized by Mehmet Esen [55] having a vacuum-tube collector with heat pipes containing different refrigerants, and the cooker realized by Sharma et al. [56] was based on the evacuated tube solar collector with a thermal energy storage system. Another example is the cooker employing flat-plate collectors with the possibility of indoor cooking [57,58].

Solar cookers cannot work when there is insufficient or no-sunshine. To enable late evening cooking, the cookers should be used with thermal energy storage. This subject interested many researchers in past years, and intensive efforts have been made to study and analyze this viable option. Phase change materials (PCMs) were considered the best solution [59–70].

3. Thermal performance analysis and test procedures of solar cookers

Solar energy is a generously available and environmentally clean source of energy, cooking with such energy has numbers of advantages. More people can be attracted towards the solar cooking by improving the performance of solar cookers [49]. These performances can be determined by an elaborate analysis of the optical and thermal characteristics of the cooker materials and the cooker design or by experimental performance testing under different operating conditions [6]. There are some performance parameters that have been adopted all over the world such as standard cooking power (P_s), first figure of merit (F_1), second figure of merit (F_2), energy (η) and exergy efficiency (ψ) etc. These parameters have been widely analyzed by many researchers and are used for evaluating the performance of solar cooking devices.

3.1. Mullick method

Mullick et al. [71] presented a method to analyze the thermal performance of solar cookers. According to this method, two

figures of merit can be calculated. The first figure of merit F_1 is determined by stagnation test at no-load conditions using following expression:

$$F_1 = \frac{T_{ps} - T_{as}}{\mathrm{IG}} \tag{1}$$

where T_{ps} is maximum absorber plate temperature, T_{as} is ambient air temperature (at stagnation) and IG is insulation on a horizontal surface at the stagnation time (in W/m²).

The second figure of merit F_2, is obtained from the full load water heating test as follows:

$$F_2 = F'\eta_O C_R = \frac{F_1(\mathrm{MC})_w}{A_c \Delta t} \ln\left[\frac{1-(1/F_1)(T_{wi}-\overline{T}_a)/\overline{\mathrm{IG}}}{1-(1/F_1)(T_{wf}-\overline{T}_a)/\overline{\mathrm{IG}}}\right] \tag{2}$$

where F' is heat exchange efficiency factor, η_O is optical efficiency, C_R is heat capacity ratio, M is the mass of water, C is the heat capacity of water, A_c is absorber plat area, Δt is time interval, T_{wi} is initial temperature of water, T_{wf} is final temperature of water, $\overline{T}_a$ is average ambient air temperature and $\overline{\mathrm{IG}}$ is the average solar radiation on horizontal surfaces.

The standard boiling τ_{boil} which is the time that cooker needs to heat an amount of water from ambient temperature to 100 °C as suggested by Mullick et al. [71] is expressed as follows:

$$\tau_{boil} = \frac{F_1}{F_2}\frac{(\mathrm{MC})_w}{A_c} \ln\left[1-\frac{1}{F_1}\left(\frac{100-\overline{T}_a}{\overline{\mathrm{IG}}}\right)\right] \tag{3}$$

A high value of F_1 indicates good optical efficiency and low heat loss factor. A high value of F_2 indicates good heat exchange efficiency factor F', good optical efficiency η_o, and low heat capacity of the cooker interiors and vessels compared to a full load of water. Their study reveals that F_1 to be in the range 0.12–0.16 whereas F_2 should be in the range of 0.254–0.490.

3.2. Funk's international standard

Funk [72] proposed an international standard for testing solar cookers to estimate cooking power (P) as follows:

$$P = \frac{(\mathrm{MC})_w \Delta T_w}{\Delta t} \tag{4}$$

where $(\mathrm{MC})_w$ is product of the mass of water and its specific heat capacity, ΔT_w is temperature difference of water and Δt is the time interval.

A standard cooking power expression P_s was also developed by Funk [72] and is given as follows:

$$P_s = \frac{700(\mathrm{MC})_w \Delta T}{600\overline{\mathrm{IG}}} \tag{5}$$

It is clear that the reference illumination intensity level should be 700 W/m² for calculating the standard cooking power [72]. From Funk's results, it was observed that the cooking power curve found by using the international test standard is a useful device for interpreting the capacity and heat storage ability of a solar cooker.

3.3. Energy and exergy analysis

Analysis of energy and exergy is another way to evaluate the performance and comparing solar cookers. As reported by Panwar et al. [11], energy analysis based on the first law of thermodynamics, i.e., net heat supplied converted in order to work. Energy analysis thus ignores reductions of energy potential. Its analysis can provide sound management guidance in those applications in which usage effectiveness depends solely on energy quantities. Thus, energy analysis is suitable for the sizing and analyzing of the systems using only one form of energy [73].

Panwar et al. [10] also mentioned in their review, that the term exergy is defined as the maximum amount of useful works that can be obtained from a system [74–76]. The rational efficiency based on the concept of exergy is a true measure of the performance of a thermal system. This is based on the second law of thermodynamics and the concept of irreversible entropy production [77,78]. It is a useful tool for improving the performance of the system by determining the magnitude of energy waste and losses in the system.

The energy efficiency η of a solar cooker is defined as the ratio of cooker output energy E_o (increase of energy of water due to temperature rise) to the energy input E_i (energy of solar radiation) and is calculated as follows [79]:

$$\eta = \frac{E_o}{E_i} = \frac{(\mathrm{MC})_w(T_{wf}-T_{wi})}{\mathrm{IG}\Delta t A_{sc}} \tag{6}$$

where E_o is the energy output of the solar cooker, E_i is the energy input of the solar cooker, M and C are the mass and specific heat capacity of the water, respectively. T_{wf} and T_{wi} are the initial and final temperatures of water in the time interval Δt, A_{sc} is the intercept area of solar cooker, IG is the total instantaneous solar radiation.

The exergy efficiency ψ is defined as the ratio of cooker output exergy E_{xo} (increase of exergy of water due to temperature rise) to the exergy input E_{xi} (exergy of solar radiation). Thus, the exergy efficiency for a solar cooker was obtained by the following relation [79]:

$$\psi = \frac{E_{xo}}{E_{xi}} = \frac{(\mathrm{MC})_w[(T_{wf}-T_{wi})-T_{ra}\ln(T_{wf}/T_{wi})]}{\mathrm{IG}\Delta t[1-(4T_a/3T_s)]A_{sc}} \tag{7}$$

It is necessary to determine the exergy of incoming solar radiation for conducting second law analysis of solar cookers. In this context, the Petela [80] expression, which has the widest acceptability, can be used to calculate the exergy of solar radiation as the exergy input to the solar cooker, and is expressible through Eq. (8).

$$E_{xi} = \mathrm{IG}\Delta t\left[1-\left(\frac{4T_a}{3T_s}\right)\right]A_{sc} \tag{8}$$

The sun's black body temperature of 5762 K results in a solar spectrum concentrated primarily in the 0.3–3.0 µm wavelength band [81]. Although the surface temperature of the sun T_s can be varied on the earth' surface due to the spectral distribution, the value of 5800 K must be considered for T_s.

Ozturk [82] also suggested the instantaneous exergy efficiency for solar cookers and is given by the following expression:

$$\psi = \frac{E_{xo}}{E_{xi}} = \frac{(\mathrm{MC})_w[(T_{wf}-T_{wi})-T_{ra}\ln(T_{wf}/T_{wi})]}{\mathrm{IG}\Delta t[1+1/3(T_a/T_s)^4-4/3(T_a/T_s)]A_{sc}} \tag{9}$$

4. Recent studies and development in solar cooking system designs

4.1. Box-type cookers

In 2000s, researchers demonstrated interest in developing new designs of solar box cookers in order to optimize their thermal performance and efficiency. In, the early 2012, Mahavar et al. [83] presented the design development and thermal and cooking performance studies of the novel Single Family Solar Cooker (SFSC). Complete theoretical consideration for the fabrication of the SFSC was also presented. During testing, the highest plate stagnation temperature under no-load condition was approximately 144 °C. The values of two calculated figures of merits F_1 (0.116 °C m²/W) and F_2 (0.466) indicate that the cooker can be used

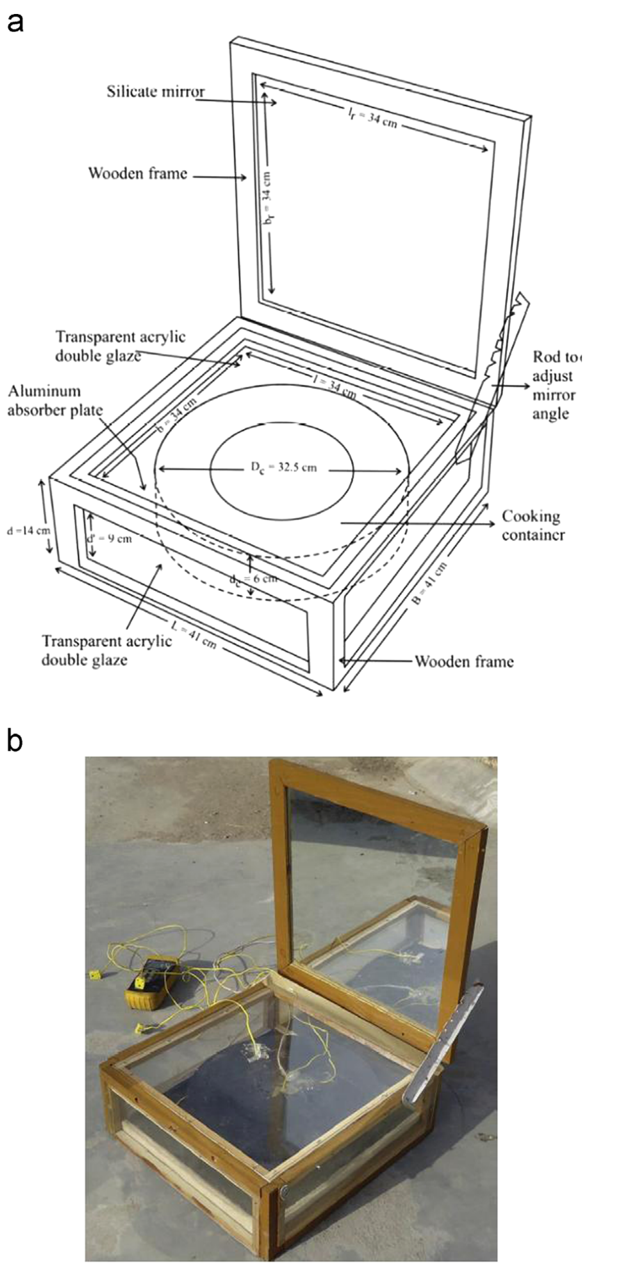

Fig. 3. Solar rice cooker [84]: (a) schematic diagram; (b) experimental arrangement.

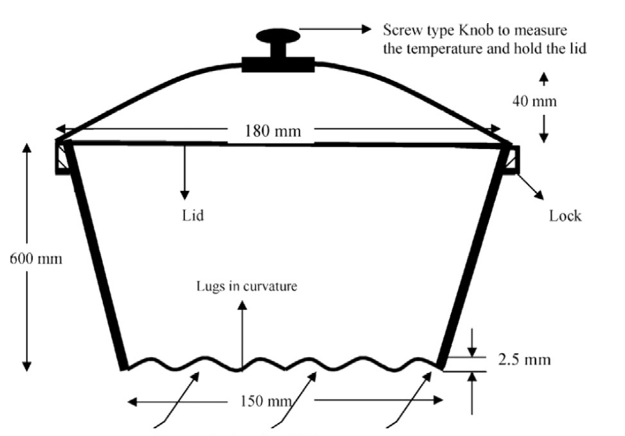

Fig. 4. Schematic view of a modified cooking vessel for a solar box cooker [6].

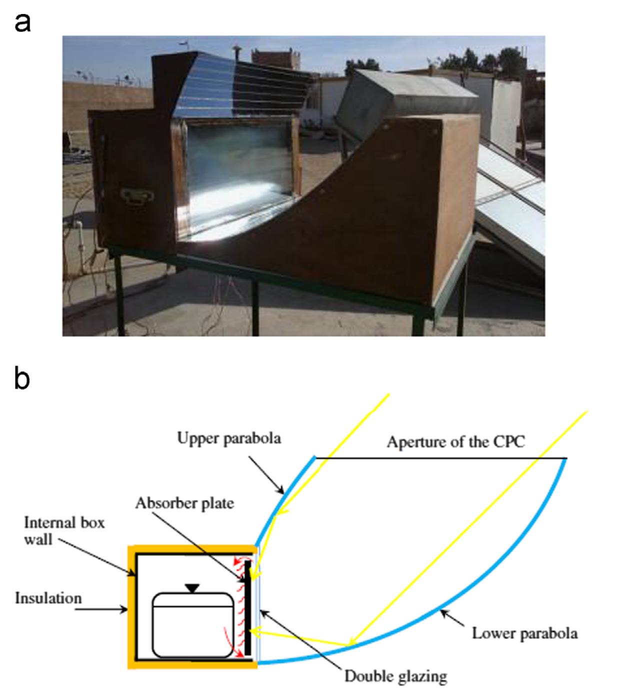

Fig. 5. New box-type solar cooker realized by Harmim et al. [85,86]: (a) a photograph of the prototype; (b) schematic sketch showing the box cooker employing an asymmetric compound parabolic concentrator.

for consecutive cooking on a sunny day. The values of the initial cooking power and heat loss coefficient at a temperature difference of 50 °C are within the range of these parameters obtained by Funk [72] for small-sized well-insulation solar cookers. In continuation of his work, Mahavar et al. [84] fabricated a Solar Rice Cooker (SRC) based on a theoretical model, and testing has been performed on various days under different weather conditions. The Schematic diagram of the SRC is illustrated in Fig. 3a. The value of the available solar power varies from 82 to 120 W, and its average value is about 107.8 W for the duration of 10:00 to 15:00 solar time. The rice-cooking time for the first and second meal is found to be 2 h and 2 h 20 min respectively. The fabricated Solar Rice Cooker as shown in Fig. 3b was found to be able to cook 0.4 kg rice twice during the solar hours on a clear day.

Cooking vessel is one of the most important components of a solar box cooker. In this context, Harmim et al. [44] conducted a comparative experimental study of a box-type solar cooker with two different cooking vessels: the first one conventional and the second one identical to the first in shape and volume but its external lateral surface augmented with fins. Adding fins improve the heat transfer from the internal hot air of the cooker towards the interior of the vessel. The vessels were made of aluminum and painted black. They found that cooking time can be reduced by using a finned cooking vessel. In the year 2011, Saxena et al. [6] proposed in their thermodynamic review a new modified cooking vessel as shown in Fig. 4 to reduce the cooking time taken by a solar box cooker. The modified cooking vessel was equipped with a series of lugs in a curvature form at the bottom of the vessel for better heat transfer. The lid becomes hot and generates a current of hot air, which circulates inside the box cooker. A heat transfer between food and the lid takes place by convection in the air layer between the food and the lid. During testing and in order to measure the temperature of cooking fluid stored in the modified cooking vessel, a lid holder removable knob has been provided on the top of cooking vessel. It was observed from the tests that the modified cooking vessel was able to achieve good cooking temperature in less timing and to reduce the cooking time

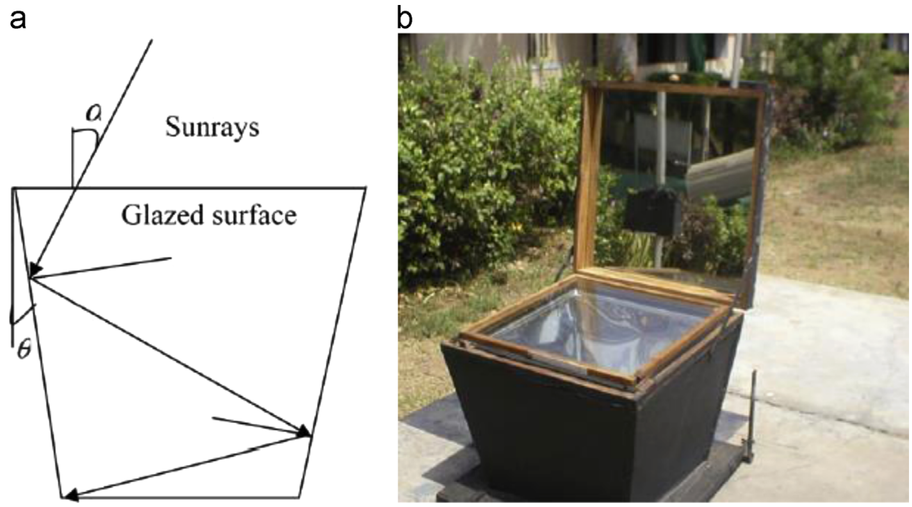

Fig. 6. Truncated pyramid cooker constructed by Kumar et al. [90,91]: (a) the schematic diagram; (b) the photographic view.

considerably than a conventional cooking vessel. The cooking power has been also improved from 70.60 W (conventional vessel) to 79.80 W for the new vessel of solar cooker.

In 2012, Harmim et al. [85,86] designed and constructed a new box-type solar cooker as shown in Fig. 5a. The new box cooker is equipped with an asymmetric compound parabolic concentrator (CPC) as the booster reflector cooker. A detailed description of the realized cooker is illustrated in Fig. 5b. A mathematical model was developed and the effects of various parameters; such as solar radiation, load of water and clouds on the dynamic behavior of the cooker were studied. The experimental study, conducted in winter and summer seasons, shows that the proposed cooker presents successful thermal performance without having recourse to tracking towards the sun. For the experimental stagnation test, the first figure of merit F_1 was calculated as 0.1681 m² kW^{-1} with values of $T_{ps}=140.5$ °C, $T_{as}=16.5$ °C and IG = 737.5 W/m². The corresponding value for F_2, when heating of 1 kg of water was calculated as 0.3295, with values of $T_{wi}=60$ °C; $T_{wf}=90$ °C; $\overline{T}_a=17.20$ °C and $\overline{IG}=725.54$ W/m². In their next work and in order to improve the cooker effectiveness, the authors suggested to make some changes to the internal geometry of the cooker box and the shape of the absorber plate [86].

During the same year, Joshi et al. [87,88] described a methodology of optimization of cooking systems to enhance the efficiency from the conventional level of 15–20% to 65–75%. For this purpose, they developed an efficient novel design of cooking systems with cooking equipment, which gained energy from condensing steam on the outside surface, and the cooking load received heat by the mode of natural convection. The CFD results indicated that the optimum heat flux depends upon the balance between the rate of heat supply and rate of heat uptake by the cooker contents. The heat flux values were found to be in the range of 83,680–104,600 kJ/h m².

Solar cookers should be used with thermal energy storage materials to allow late evening cooking PCM is the best solution to store the solar energy during sunshine hours. Chen et al. [62] investigated phase change materials (PCMs) used as the heat storage medium for solar box cookers. The selected PCMs were magnesium nitrate hexahydrate, stearic acid, acetamide, acetanilide, and erythritol. They also presented a two-dimensional model based on the enthalpy approach for predicting the thermal performance of the storage system. As a result, stearic acid and acetamide were found to have a good compatibility with the latent heat storage system; thus, they should be used as storage media in a box-type solar cooker to cook and/or to keep food warm in the late evening. It was also found that the initial temperature of PCM does not have very important effects on the melting time. In the following year, Sharma et al. [67,89] discussed the thermal storage technology for box solar cooker based on their reviews. They concluded that with the help of the heat energy storage unit, food could be cooked late in the evening. The use of a latent heat storage system with phase change materials (PCMs) has been also analyzed.

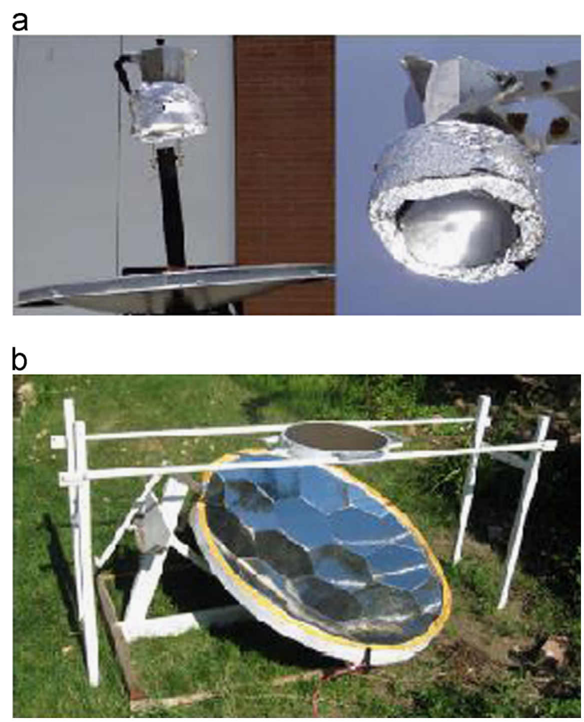

Fig. 7. Concentrating cookers with dish and Umbrella design reflectors (a) experimental setup scheme and photograph view of coffeemaker system realized by Sosa-Montemayor et al. [92]; (b) solar fryer diagram and photo of the prototype setup with pan cover removed developed by Gallagher [93].

The ranges of solar devices with multipurpose applications have also been widely investigated. Kumar et al. [90] designed, fabricated, and tested a multipurpose domestic solar cooker cum dryer based on truncated pyramid geometry at the Sardar Patel Renewable Energy Research Institute of India. This concept (Fig. 6a) concentrates the incident light radiations towards the bottom. The glazing glass surface on the top facilitates the

Fig. 8. Concentrating solar cooker and water heater operating in the cooking mode, built and tested by Badran et al. [94].

Fig. 9. Testing of the K-10 concentrating cooker developed by Grupp et al. [95].

trapping of energy inside the cooker. The authors recommended minor modifications to achieve higher temperatures and to reduce cooking times. Later, Kumar et al. [91] designed, constructed and tested a truncated pyramid geometry-based multipurpose solar device (Fig. 6b) which could be used for domestic cooking as well as water heating. Cooking tests were performed across different seasons. The maximum absorber plate stagnation temperature was determined to be 140 °C. The figure of merits F_1 and F_2 were calculated about 0.117 °C m²/W and 0.467, respectively, meeting the standards prescribed by the Bureau of Indian Standards for solar box-type cookers.

4.2. Concentrating-type cookers

In the past decades, concentrating-type solar cookers have also been a subject of investigations conducted by many researchers. Sosa-Montemayor et al. [92] presented, realized, and also tested a solar coffee maker. It is a novel solar concentrating application that consists of a satellite TV mini-dish concentrator coupled to a stovetop espresso coffee maker. The experimental setup scheme and photographic view of this coffee system are illustrated in Fig. 7a. The authors presented a theoretical model for the evolution of the water temperature inside the coffee brewing system. That model was validated via a comparison with actual experimental results and underlined by results that indicate the coffee brewing system takes 30–50 min to brew coffee. This time is too long, but that detail is not critical because the theoretical model was good at predicting the temperature evolution of the thermodynamic system. The suggested system modifications by the authors will permit achieving a useful solar coffee maker. In early 2011, Gallagher [93] designed, developed, and tested a prototype for a solar fryer with the goal of producing an effective, robust, safe, and affordable solar fryer for solar cooking of injera bread. A mirror below the pan directs the radiation to the pan bottom, which is coated black (Fig. 7b). The mirror uses flat, hexagonal panels of aluminized-mylar to provide uniform illumination across the majority of the pan bottom. The mirror mount allows 8 h/day operation with a single mirror-angle adjustment, plus a seasonal mounting adjustment for full-year use. The proposed design is also scalable to any desired pan size. The prototype provides approximately 640 W of heating power, which allows the cooking of about 30 kg of injera bread per clear day for 150 people.

In 2010, Badran et al. [94] designed, built and tested a portable solar cooker and water heater. A normal satellite dish 150 cm diameter in size was used as a concentrator for solar radiation. The surface of the dish was covered with reflective aluminum foil used to concentrate the solar energy on a cooking pot in two operating modes (cooking food and heating water). The device operated in the cooking mode is shown in Fig. 8. It was concluded from their experimental results that in the cooking mode, a 7 kg of water at 20 °C was brought to a boil in 1 h. Putting the pot inside a glass box reduced the time required for boiling temperature to 40 min and cooking power increased by 275%. The efficiency for the cooking process using the glass box cover was almost twice that of using the process without the cover. In the water heating mode, the device was able to heat 30 kg of water from 20 °C to 50 °C in 2½ h in November. The highest efficiency obtained for this mode was 77%, and the uncertainty of measuring the cooking power and the efficiency in both modes range between $\pm 1.4\%$ and $\pm 1.7\%$.

Grupp et al. [95] designed and developed a metering device for the determination of a solar cooker use rate by a novel metering device (Fig. 9). The device allowed the recording of food temperature, ambient temperature and irradiance. A solar cooker use meter records actual cooking history in terms of quantity of food successfully cooked, allowing for the appraisal of fuel savings and GHG emission reduction, when compared with other cooking options. Metering results were compared with actual conditions for two types of solar cookers and found to be in agreement.

Purohit and Purohit [96–98] experimentally investigated a box-type and parabolic concentrating-type solar cookers with the aim to estimate the instrumentation error for an effective quality control which is essential for a large-scale dissemination of these devices. For the characterization, they carried out a large number of experiments using various test procedures in the climatic conditions of New Delhi, India, under different climatic and operating conditions around the year. The technical specifications of the instrumentation used in measurements are summarized in Table 1. The effect of instrumentation error has been evaluated the maximum on second figure of merit, optical efficiency factor, and standardized cooking power. It has been estimated that instrumentation cause 1.0–5.5% error on the thermal performance parameters of solar cookers. Based on this study and in order to ensure the technological appropriateness of the solar cookers the test methods are critically important. It is recommended that appropriate ranges of the performance indicators and accuracies of the measuring instruments must be defined in test standards of solar cookers [98].

Hybridization of solar cooking systems is also a possible option for cooking. Prasanna and Umanand [99,100] proposed and developed a hybrid solar cooking system where solar energy was brought to the kitchen. The energy sources were combination of

Table 1
Details of instrumentation used for testing of box and paraboloid concentrator-type solar cookers [98].

Parameter measured	Instrument used	Type/make	Range	Least count
Total solar radiation	Eppley radiometer	Model PSP 24319F-3	0–1200 W/m²	1.0 W/m²
Diffuse solar radiation	Eppley radiometer	Model PSP 24319F-3	0–1200 W/m²	1.0 W/m²
Ambient air temperature	Thermocouple	Copper-constantan	0–600 °C	0.05 °C
Cooker tray temperature	Thermocouple	k-type	0–600 °C	0.05 °C
Water temperature	Thermocouple	Copper-constantan	0–600 °C	0.05 °C
Weight (water and cooking pots)	Electric balance	–	0–30 kg	0.001 kg
Cooking time	Data-acquisition system	–	–	1.0 s
Dimensions	Meter scale	–	0–2.0 m	0.001 m

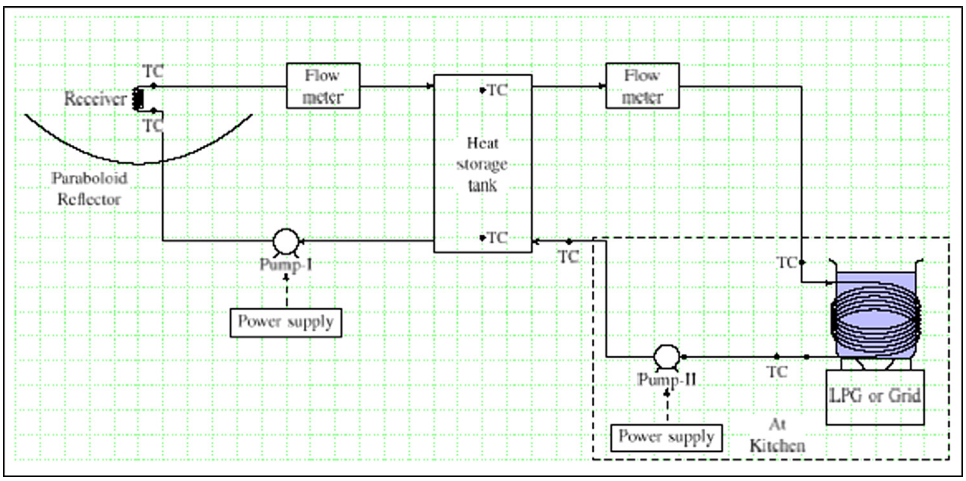

Fig. 10. Block diagram of experimental setup for the hybrid solar cooking system developed by Prasanna and Umanand [99,100].

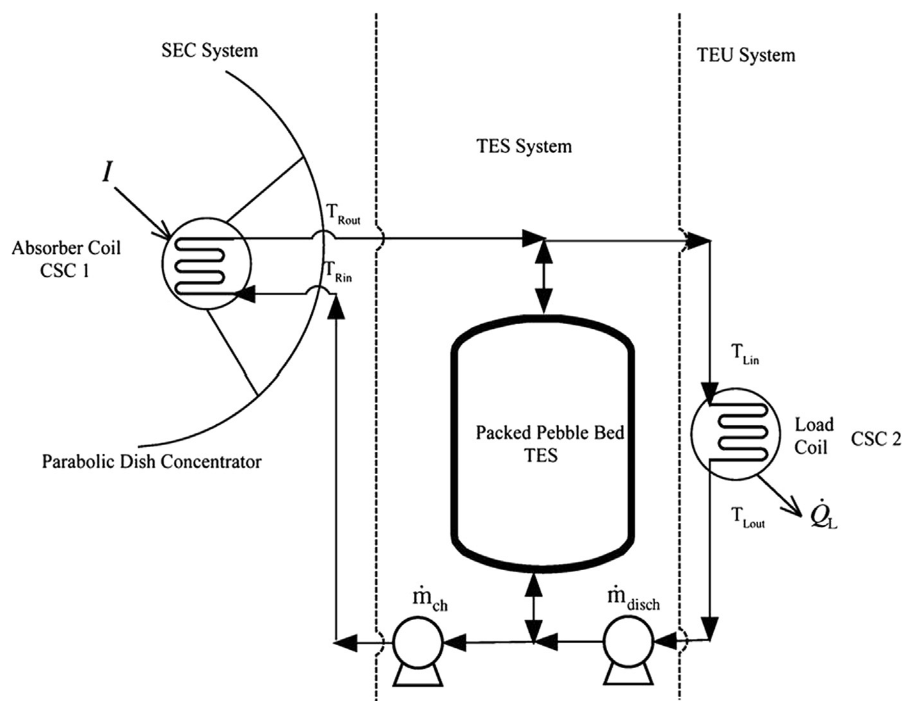

Fig. 11. Conceptual diagram of the indirect solar thermal energy storage and cooking system proposed and tested by Mawire et al. [104].

the solar thermal energy and Liquefied Petroleum Gas (LPG). Solar energy is transferred to the kitchen via a circulating fluid. The block diagram of this experimental setup is shown in Fig. 10. Energy collected from the solar thermal collector was optimized by dynamically varying the flow rate using the maximum power point tracking (MPPT) techniques. The concept of MPPT was validated through simulation and experimental results. These results show that cooking can be carried out at any time of the day with time needed very comparable to that for conventional systems.

In recent years, PCM has enhanced the performance of solar energy collectors within the limitations of thermodynamics [101].

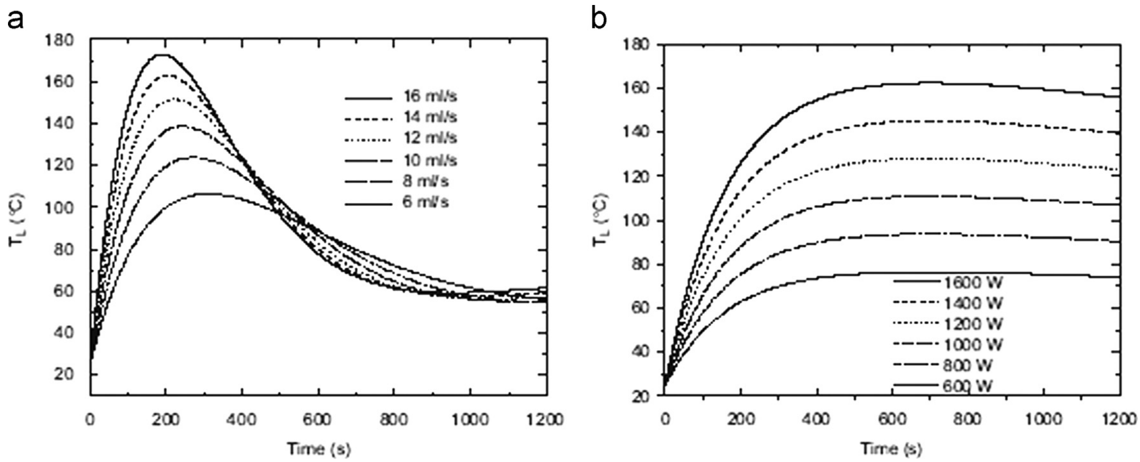

Fig. 12. Temperature (T_L) profiles obtained for 1 l of olive oil (a) at different constant discharging flow rates. T_L falls to 60 °C for all cases; (b) at different controlled load powers [104].

Fig. 13. Cooker view in operation with focused sun on utensil realized by Lecuona et al. [105].

El-Sebaii et al. [61,102] used acetanilide and magnesium chloride hexahydrate as PCM storage media integrated indirect solar cooker. On the basis of the obtained results, it can be inferred, that, acetanilide is a promising PCM for cooking indoors, and during low intensity solar radiation periods, they achieved a stagnation temperature of 134 °C [61]. At Northwest University of South Africa in the early 2010, Mawire et al. [103,104,66] presented a mathematical model for an oil/pebble-bed thermal energy storage system (TES) to perform discharging simulations in an indirect solar cooker. The model was validated with experimental results, and good agreement was found between the simulation and the experiment. The schematic diagram of experimental setup for the indirect solar TES system is illustrated in Fig. 11. Results of the TES system were presented using two methods (Figs. 12a and b). The first method discharged the TES system at a constant flow rate. Using such a method, the experimental results indicate a higher rate of heat utilization, which is undesirable for the cooking process. The second method changed the flow rate in order to obtain the desired power at a constant load inlet temperature. The controlled load power discharging method has a slower initial rate of heat utilization, but the maximum cooking temperature was maintained for most of the discharging process, this method of discharging proved more beneficial to the cooking process [104].

Recently, Lecuona et al. [105] developed 1-D model for an innovative portable solar cooker of the concentrating parabolic-type with PCM based heat storage as shown in Fig. 13. The utensil is formed by two cylindrical cooking pots, filled between them with a phase change material (technical-grade paraffin or erythritol). An example of results is illustrated in Fig. 14. The obtained results for climatic conditions of Madrid indicate that it is possible to cook lunch and dinner for a family during sunny summer and winter days. Using the retained heat it is also possible to cook the breakfast of the next day. It is also found that 100 °C phase change paraffin seems better adapted for the defined duty than a PCM like erythritol.

4.3. Exergetic assessment of solar cookers

Several theoretical and experimental studies were carried out concerning energy and exergy efficiencies of solar cookers. Kumar et al. [106] investigated the time variation of instantaneous exergy output and energy output as a function of its temperature and also of the instantaneous ambient temperature for truncated pyramid type solar box cooker. The water temperature inside the vessels reached 90.6 °C from 60 °C in 70 min whereas the initial water and ambient temperatures were 43.18 °C and 33.43 °C, respectively. The maximum and minimum energy gained from water inside the solar cooker was 20.8 kJ and 7.5 kJ, corresponding to maximum and minimum values of insulation 929 W/m² and 376 W/m², respectively. Recently, Kumar et al. [107] developed a uniform test standard for evaluating the thermal performance of the cookers irrespective of their geometrical construction. They plotted graphs between exergy output and temperature difference for solar cookers of different designs resembling a parabolic curve. The proposed parameters can lead to development of unified test protocol for solar cookers of diversified designs.

Panwar et al. [108] experimentally evaluate the energy and exergy efficiencies of the animal feed solar cooker. The cooker was made of cement, bricks, glass covers, and a mild steel absorber plate. The overall dimensions of the hot box were 900 mm × 900 mm × 190 mm. A schematic of a solar cooker for animal feed is illustrated in Fig. 15a, and its side view is presented in Fig. 15b.

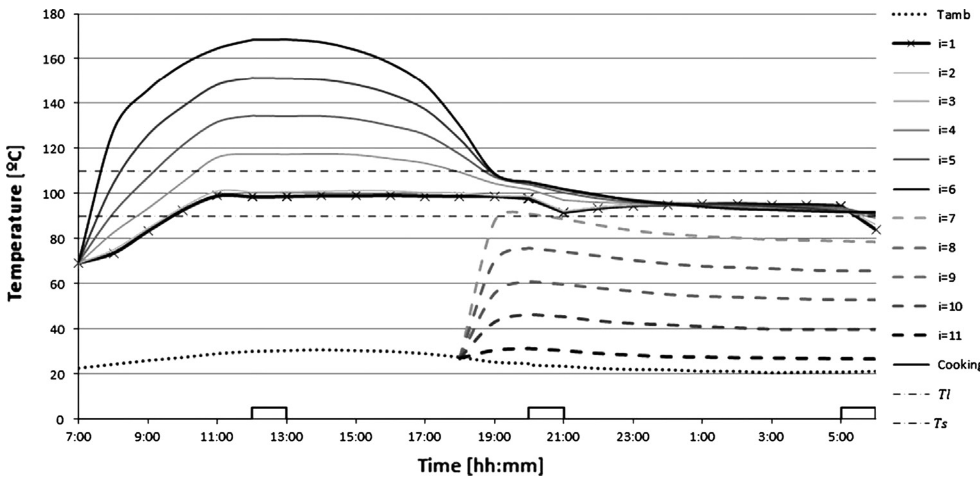

Fig. 14. Time evolution of temperatures versus solar time for July the 15th, PCM is paraffin [105].

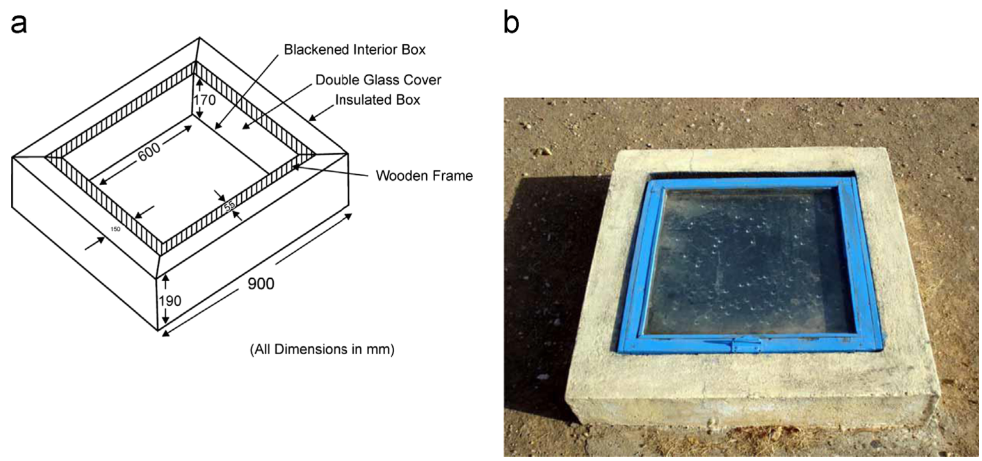

Fig. 15. Animal feed solar cooker proposed by Panwar et al. [108]: (a) dimensions; (b) side view of the cooker.

Table 2
Results of the energy and exergy analysis for the animal feed solar cooker proposed by Panwar et al. [108].

Variables	Values	
	Minimum	Maximum
Water temperature (°C)	38.9	72.2
Temperature difference (°C)	2	29.8
Energy input (kJ)	161.52	196.81
Energy output (kJ)	1.89	49.4
Exergy input (kJ)	148.52	184.44
Exergy output (kJ)	0.11	2.72
Energy efficiency (%)	1.12	29.78
Exergy efficiency (%)	0.07	1.52

The energy output of this cooker ranges from 1.89 to 49.4 kJ, whereas the exergy output ranges from 0.11 to 2.72 kJ during the same time interval. The energy efficiency of the cooker varies between 1.12% and 29.78% while the exergy efficiency varies between 0.07% and 1.52% during the identical period. The results of energy and exergy analyses are presented in Table 2.

More recently, in the year 2013, Panwar [109] developed a thermal model of an animal feed solar cooker (AFSC), and its results were validated experimentally. The experiment was conducted for 9 months and found that the developed model is capable of predicting the reasonable values of temperature. The value of the correlation coefficients for all months was 0.999. The theoretical values of vessel fluid temperature are 2–3 °C higher than the experimental values. An example of cooker performance is illustrated for May month in Fig. 16. It is noted that considerable temperature gain by vessel fluid is observed during this month; hence, the cooking of feed can be faster than in other months. Energy and exergy assessment of the cooker was also carried out. The experimental energy and exergy efficiency varied in the range of 23.19–28.25% and 1.79–2.47%, respectively. The corresponding theoretical efficiency varies in the range of 24.22–28.33% and 1.97–2.88%, respectively. The results of energy and exergy analyses for AFSC are presented in Table 3.

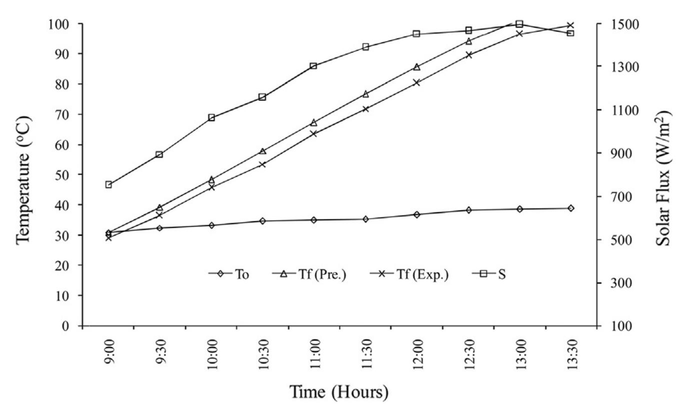

Fig. 16. Experimental and predicted water temperature for animal feed solar cooker in May month, investigated by Panwar [109].

Table 3
Performance of animal feed solar cooker [109].

Month	Input (kJ/day)		Output (predicted) (kJ/day)		Output (experimental) (kJ/day)		Efficiency (predicted) (%)		Efficiency (experimental) (%)	
	Energy	Exergy	Energy	Exergy	Energy	Exergy	Energy	Exergy	Energy	Exergy
October 2011	588.23	549.03	144.15	13.77	141.89	12.24	24.51	2.51	24.12	2.23
November 2011	477.15	445.81	125.96	9.20	122.12	8.03	26.40	2.06	25.59	1.80
December 2011	461.13	431.52	120.88	7.66	117.00	7.72	26.21	2.01	25.37	1.79
January 2012	414.98	388.11	117.55	7.66	117.24	6.97	28.33	1.97	28.25	1.80
February 2012	501.73	468.78	137.33	10.48	133.75	9.40	27.37	2.24	26.66	2.00
March 2012	621.64	580.33	157.04	15.36	153.76	13.64	25.26	2.65	24.73	2.35
April 2012	655.75	611.23	164.18	16.85	157.94	14.74	25.04	2.76	24.09	2.41
May 2012	706.20	657.56	171.01	18.93	163.76	16.27	24.22	2.88	23.19	2.47
June 2012	585.61	545.23	142.92	13.74	143.99	12.67	24.41	2.52	24.59	2.32

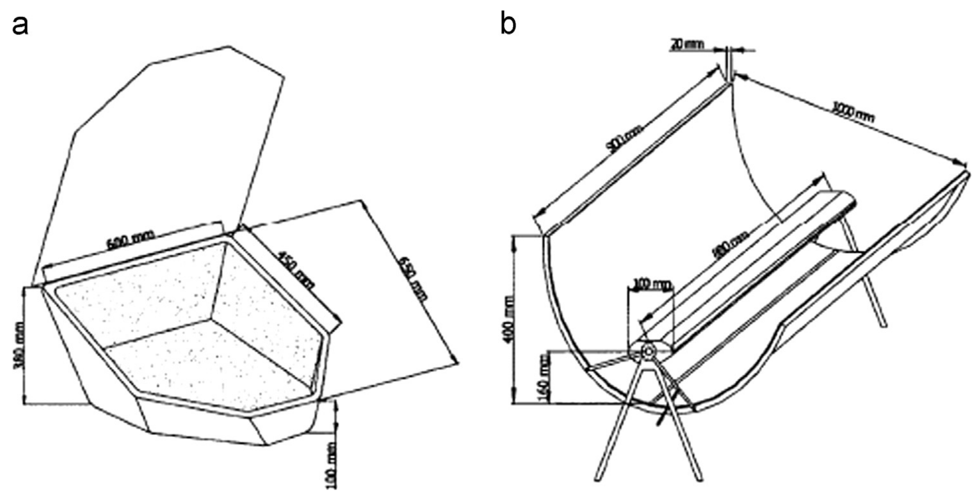

Fig. 17. The dimensions of the solar box (a) and parabolic (b) cookers experimentally studied and compared by Ozturk [79].

Mawire et al. [110] discussed about an oil-pebble bed thermal energy storage system for an indirect solar cooker using energy balance equations. A dish-type solar concentrator was used for this purpose. Energy and exergy analyses were carried out using two different charging methods to predict the performance of the system. The first method had a constant flow rate of heat transfer fluid, and the second method carried out a constant charging temperature. It was determined that higher exergy rates were obtained with the constant temperature method with higher levels of the solar radiation.

In the end of 2009, Shukla [111] compared the energy and exergy efficiencies of community size and domestic size paraboloidal solar cookers. From the results, it was observed that the energy output of the community solar cooker varied between 2.73 to 43.3 W and 7.77 W to 33.4 W for the domestic solar cooker. The exergy output for community solar cooker was in the range of 1.92 to 2.58 W, whereas for the domestic solar cooker, it varied from 0.65 to 1.45 W. The energy efficiency of the community, solar cooker varied from 8.3% to 10.5% and for the domestic solar cooker, it varied from 7.1% to 14.0%.

In Turkey, Ozturk [82,112–114] conducted several experimental research projects on solar cookers and analyzed the performance parameters in terms of thermodynamic laws. Petela [80] inspired by Ozturk's study, investigated a solar parabolic cooker, of the cylindrical trough shape, from the perspective of exergy. It was shown that the exergy efficiency of the parabolic cooker was found to be relatively very low (approximately 1%) while the energy efficiency ranged from 6% to 19%. Later, an experimental comparative study on energy and exergy efficiencies for solar boxes and parabolic cookers (Figs. 17a and b) was conducted by Oztruk [79]. It was found that the average daily water temperature difference from 10:00 to 14:00 solar time was 42.97 and 31.56 K in the SBC and SPC, respectively. From the results of this study, it was seen that the difference between the results of energy and exergy analyses is significant. It was also found that, during the experimental period, the energy and exergy efficiencies of the box-type and the parabolic-type cookers were in the range of 3.05–35.2%, 0.58–3.52% and 2.79–15.65%, 0.4–1.25%, respectively.

In, the early 2011, Pandey et al. [115] presented a comparative experimental study of a box-type and a paraboloid-type solar cooker based on the exergy analysis. The experiments have been carried out with cookers filled with different volumes of water and rice. Data on temperatures and solar radiation have been measured for different food stuffs on clear sky day. Comparative results are shown in Fig. 18. Fig. 18a and b illustrates the variation of efficiency and solar radiation with respect to time for one and two liters of water in the paraboloid solar cooker. On the other hand, Fig. 18c and d illustrates the variation of exergy efficiency, i.e., second law efficiency and solar radiation for one and two liters of water in box-type solar cooker. It was found from the results that the exergy efficiency increases as the volume of water increases, however, the exergy efficiency of a paraboloid solar cooker is found to be higher than that of the box-type solar cooker. It was also found that the exergy efficiency varied with the cooking stuff and water which is due to the fact that the requirement of heating varied with the food stuff.

5. Tracking devices applied in solar cooker systems

The radiation intensity falling on the solar systems is affected by the diurnal and seasonal movement of earth. Consequently, the amount of power produced by these systems is directly dependent on the quantity of solar radiation. Therefore, it is necessary to

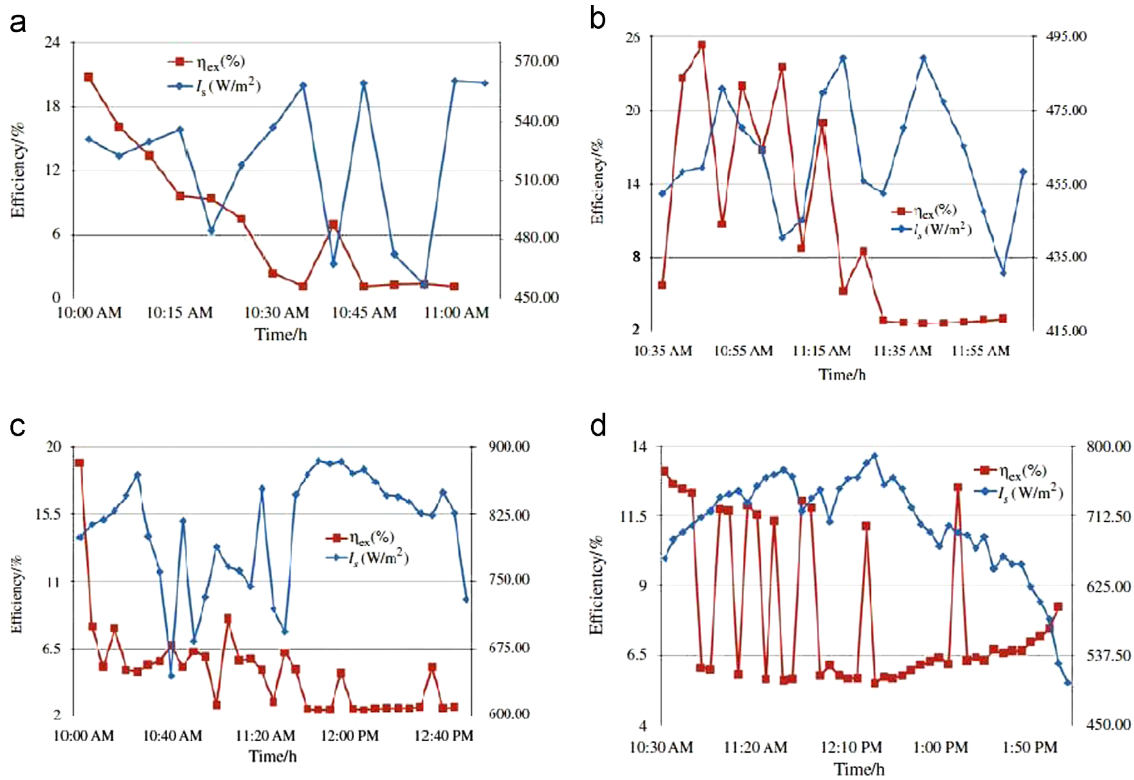

Fig. 18. Time versus exergy efficiency and solar radiation: (a) one liter of water in the paraboloid solar cooker; (b) two liters of loaded water in the PSC; (c) one liter of water in the box solar cooker; (d) two liters of loaded water in the BSC, experimented by Pandey et al. [115].

adopt solar systems based tracking devices to improve the solar energy utilization. The sun tracker is a device that moves solar systems in the best orientation possible in order to minimize the incidence angle, with the aim to keep an optimum position throughout the daylight hours. A sun tracker would allow sun following in a north–south direction (for seasonal tracking) as well as in an east–west direction (for diurnal tracking) by moving the solar system with the correct angles so that it points towards the sun continuously. As underlined by Mousazadeh et al., the use of a solar tracking system can increase the collected energy 10–100% in different periods of time and geographical conditions. Further studies show that, the solar energy gained by the sun tracking system (biaxial) is 35% higher than that of the fixed system [116].

5.1. Solar systems with tracking devices

It is well-known in literature that, sun tracking systems are usually categorized in one-axis or two-axis trackers, including mechanical or electrical devices, which are continually improved by researchers over the world. As noted by Abu-Malouh et al. [117], single axis tracking systems are considerably cheaper and easier to construct, but their efficiency is lower than that of two-axis sun tracking systems. On the other hand, some solar systems; such as point focus concentrators, require only two-axis tracking, the main advantage of two-axis tracking collectors is their higher efficiency. A large number of investigations concerning the uses of sun tracking systems (single and dual-axis) for solar applications have been performed within the past years by several researchers based on the diverse type of collectors, like photovoltaic (PV) panels [118,119], heliostat field collector (HFC) [120,121], parabolic-trough collector (PTC) [122,123], parabolic dish reflector (PDR) [124,125], compound parabolic collector (CPC) [126,127] and linear Fresnel reflector (LFR) [128,129] around the globe.

During previous years, most sun trackings study concern photovoltaic systems. In the year 2011, Parvaresh et al. [118] developed a new method to improve the efficiency of PV panels, which was applied on two-axis tracker. In this method, instead of using optical sensors, an adaptive algorithm is used to calculate azimuth and elevation angles of the sun via micro-controller. By comparing the results of this method with respect to method of optical sensors, higher PV output efficiency was achieved by using the new adaptive algorithm.

Sun tracking systems destined to concentrating applications were also deeply investigated in recent years. In 2010, a prototype of toroidal heliostat with receiver oriented dual-axis tracking was designed, modeled and realized by Guo et al. [120] as shown in Fig. 19a. A new tracking formula was presented and the accuracy of applying a simplifying approximation was analyzed. The tracking system has two rotation axis (Fig. 19b), so that the heliostat can track the sun in E–W and N–S direction. A series of dual-axis tracking formulas has been derived for the heliostat. The authors underlined that, exact tracking formulas provide a good foundation for further analysis of the heliostat tracking error. In addition, the exact tracking angles are useful for analysis and assessment of concentrated solar images on a receiver aperture [120]. In the following year, the tracking and ray tracing equations for the target-aligned heliostat for solar tower power plants was derived by Wei et al. [121].

In the Laboratory of Energy Economics at Democritus University of Thrace in Greece, Bakos [122] designed and constructed a parabolic-trough collector with the two-axis sun tracking system, which is based on the combined use of the conventional photoresistors and the programming method of control. A working principle of sensors system (photoresistors) and a proposed prototype are illustrated in Fig. 20a and b, respectively. It is concluded that the gain of the two-axis tracking system is considerable (up to 46.46%) compared with the fixed surface for operation in all weather conditions.

In early 2013, Gama et al. [130] presented an innovative work (Figs. 21a and b) which consists of a novel sun tracking system

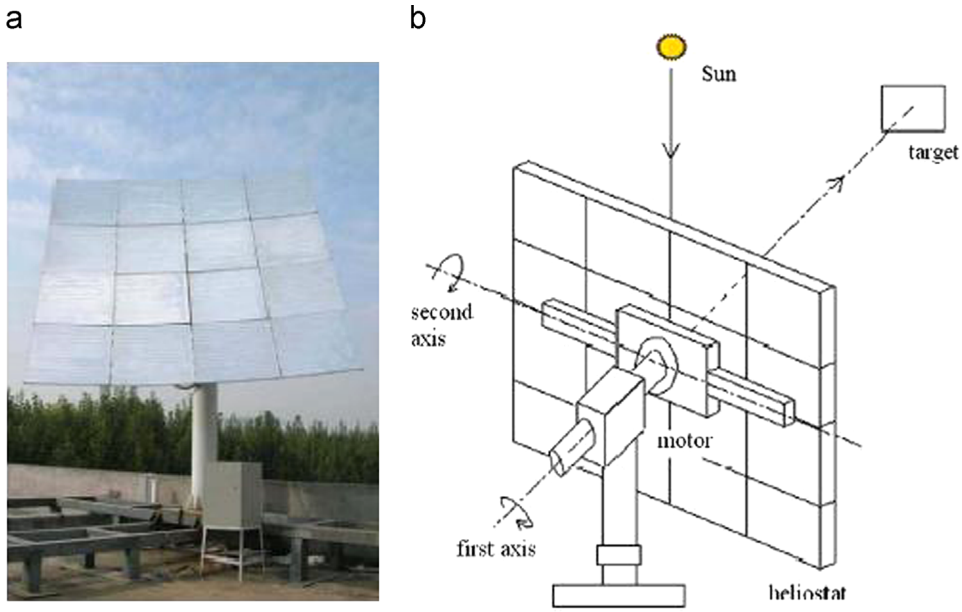

Fig. 19. Photo of the toroidal heliostat on a rooftop at Xi'an Jiaotong University in China: (a) front view showing mirror and (b) two-axis tracking system [120,121].

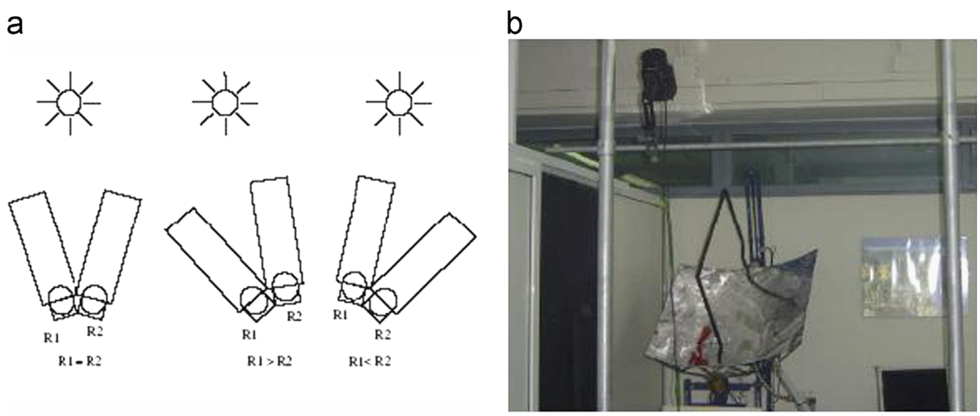

Fig. 20. Parabolic-trough collector in the Laboratory of Energy Economics at Thrace Democritus University in Greece: (a) photoresistors principle and (b) view of the prototype [122].

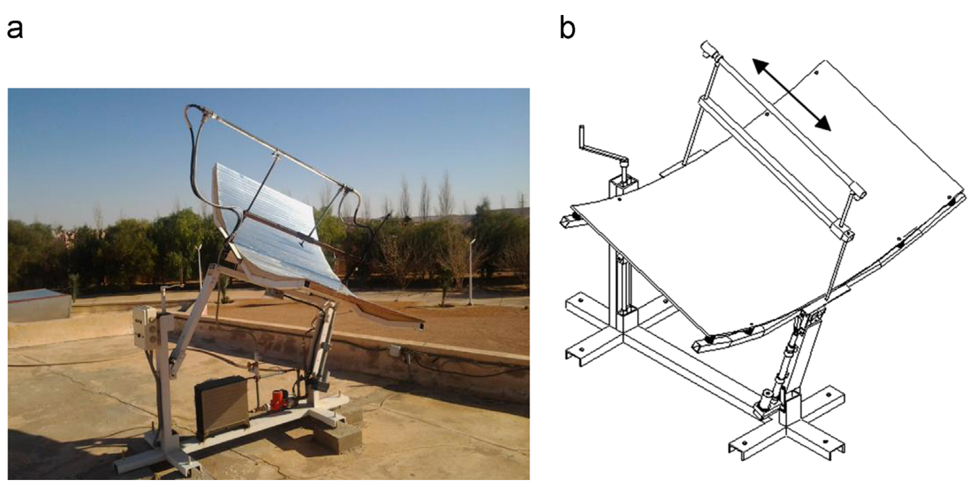

Fig. 21. Novel sun tracking system with absorber displacement for parabolic trough collectors realized by Gama et al. [130]: (a) a photograph of the prototype; (b) presentation of the movable absorber for the PTC prototype.

based on absorber displacement in order to minimize the optical losses caused by the cosine effect in parabolic troughs (PTC). A prototype of parabolic trough collector equipped with the novel tracking system is realized and tested in Ghardaîa region (32.48°N, 3.66°E, 502 m) located at Southern of Algeria. The new concept was validated through simulation using TRNSYS software and

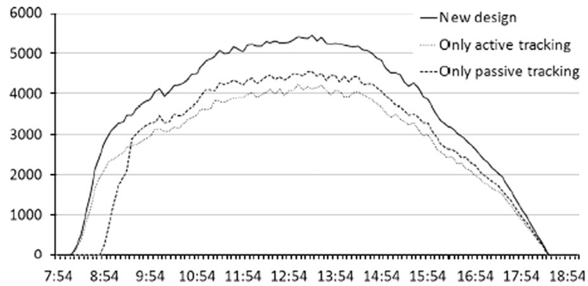

Fig. 22. Experiment result of power output from realized dish solar thermal energy [124].

experimental results. Tests on the system have proven a quite good effectiveness regarding the hard climate conditions in the south of Algeria. Comparing the obtained experimental results with simulation one, it was found that the efficiency of the new sun tracking system with reflector displacement is in between the efficiency of one and two axes sun tracking. Efficiencies close to 50% were obtained.

In the year 2012, an experimental realization was performed by Kuang and Zhang [124] to investigate the effect of using a tracking system on the solar energy output. For this purpose, a tracking system for dish solar thermal energy based on an embedded system that mixes active and passive tracking was designed and implemented. This new design uses more stability sensors so that can improve both accuracy and stability. The experiments show that the design was effective and reliable. An example of average daily power output curves is shown in Fig. 22.

Khalifa and Al-Mutawalli investigated the improvement in the performance of a compound parabolic concentrator when used with a two-axis sun tracking system. A sun tracking system of photo-transistors separated by a partition from one another and two identical CPC collector was designed, constructed and tested at Solar Energy Research Center of Baghdad. It was concluded from the tests that a two-axis tracking system may increase the energy gain of a CPC collector by up to 75% [127]. AL-Jumaily and AL-Kaysi [129] studied the performance of flat linear Fresnel lens concentrating solar radiation on two absorbers connected in series. The tracking system was constructed so that it tracks the sun in two directions. Tests were carried out to evaluate thermal and optical efficiency of the system. It was found by authors that, to get higher efficiency the collector should run with higher flow rate but the water outlet temperature will be less. It was concluded, for two directional tracking optical efficiency is constant and about 0.64%.

5.2. Solar cookers with sun tracking systems

From the review it is seen that the temperature around 100 °C is achieved in box-type solar cooker. As underlined by Lahkar and Samdarshi, this range of temperature is suitable for cooking by boiling. Such type of cookers may either fail to cook or take longer time to cook full load of food because of its inability to attain desirable temperature or to transfer heat to the content of pot at a fast rate in a given climate [49]. On the other hand, parabolic solar cookers have a concentration ratio up to 50 and therefore able to attain higher temperatures (up to 200 °C) in a short time. They do not need a special cooking vessel, unlike the box-type and are suitable for boiling and food cooking. However, parabolic cookers are not well insulated and need frequent adjust to tracking the sun and to maintain the point focus. They are usually equipped with the two-axis sun tracking system which makes the whole system complex to manufacture. Parabolic cookers also include risk of burning food because of the uncontrolled concentrated power. In last recent years, and in order to resolve some problems related to solar cooking technologies, the designs of solar cooker systems are more oriented to be equipped with sun tracking devices permitting to follow sun courses, even box types.

In 2010, Al-Soud et al. [131] designed, constructed, operated and tested a parabolic solar cooker (PSC) with automatic sun tracking system using a programmable logic controller as shown in Fig. 23a. The Variation of water temperature inside the collecting tube is shown in Fig. 24a. The experimental results reveals that using parabolic solar cooker with automatic tracking, the water temperature inside the cooker's tube reached 90 °C in a typical summer day, when the maximum registered ambient temperature was 36 °C. One year later, Abu-Malouh et al. [117] designed, realized and analyzed a spherical-type solar cooker with the automatic two-axis sun tracking system as illustrated in Fig. 23b. For this purpose, a dish was built to concentrate solar radiation on a pan that is fixed at the focus of the dish. The spherical dish tracks the sun using the sun tracking system, collects the solar energy incident on it and concentrates it using 256 concentrating mirrors. The sun tracking system is composed of the two motors; the rotation of the motors is controlled by the two-axis sun tracking system with programmable logic controllers (PLC). The inside pan temperature variation is a function of time is shown in Fig. 24b. It was observed from the results for three different days, that the temperature inside the pan reached more than 93 °C in a day where the maximum ambient temperature was 32 °C, which is suitable for cooking purposes.

Concentrating system using Fresnel lens is one of the methods able to increase the amount of absorbed solar energy. Valmiki et al. [132] designed, realized and tested a novel design solar cooking stove which uses large Fresnel lens for the concentration of sunlight (Fig. 25). The stove has a fixed heat-receiving area located at the focal point of the lens. The sunlight tracking system rotates the Fresnel lens about its focal point in both zenith and azimuth angles using two rotation arms. Since the solar tracking allows the Fresnel lens to concentrate sunlight, solar stove based Fresnel lens demonstrated high safety and efficiency with relatively low heat loss. The outdoor solar stovetop could reach a temperature of 300 °C for cooking application; solar heat collected on the outdoor stovetop could be circulated through a mineral oil loop to an indoor stovetop which reaches a temperature of 150 °C. Temperatures of the outdoor stovetop, the mineral oil inside the aluminum chamber, as well as the indoor stovetop are given in Fig. 26. Based on the realized prototype, some technical improvements are proposed to advance the technology in the future.

Recently, Farooqui [133] presented a new type of improved vacuum tube based solar cooker (Fig. 27). The proposed cooker utilizes a solar collector consisting of parallel plane rectangular glass mirror strips mounted inside a wooden frame and requiring one-dimensional solar tracking through a common driver. Thus, the greatest advantage of this cooker is that it offers fast cooking and does not require frequent manual solar tracking. Temperatures as high as 250 °C are attainable, making it suitable for water based as well as oil based cooking and frying of food. The proposed design can be either installed over the roof top of a house or near a south facing window (in countries of the northern hemisphere). Due to larger collector area, the design offers substantially higher cooking power compared to other conventional solar cookers. Experiments performed during various months of the year show substantially improved performance of the cooker all year round.

In early 2013, Farooqui [134] presented an innovative work (Fig. 28) which consists of a novel mechanism for one-dimensional tracking of box-type solar cookers along the azimuth that does not require any unavailable external power source, as the external power source is simple water. The required tracking energy is drawn from the potential energy stored in a spring attached to a water container. The requirement for tracking along the second dimension (altitude) has been eliminated through an optimized extended booster mirror. Experimental results and performance

Fig. 23. Concentrating-type cookers with sun tracker systems (a) parabolic solar cooker constructed by Al-Soud et al. [131]; (b) spherical-type solar cooker realized by Abu-Malouh et al. [117].

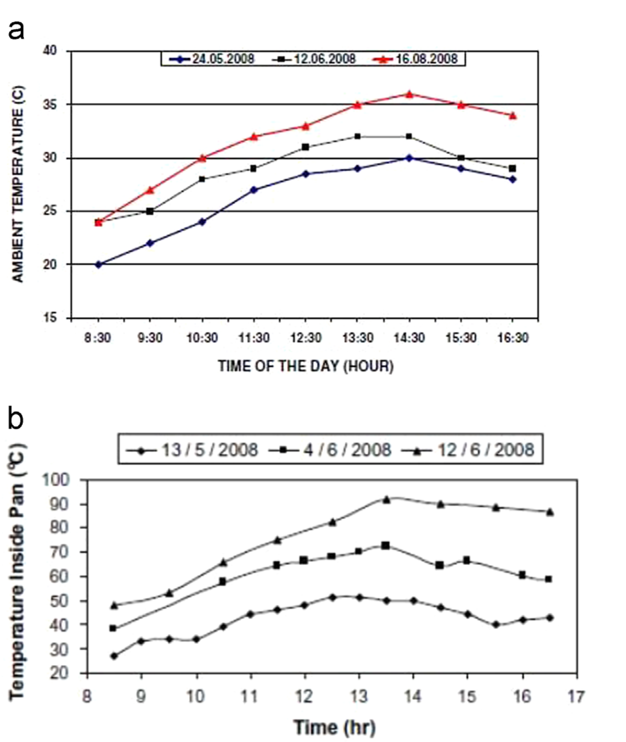

Fig. 24. Obtained results for concentrating solar cookers with sun tracking systems (a) variation of water temperature inside the collecting tube for the parabolic-type solar cooker constructed by Al-Soud et al. [131]; (b) variation of temperature inside pan for the spherical-type solar cooker realized by Abu-Malouh et al. [117].

analysis of a prototype have been included. The results indicate that if the system is set for 3 h at a time, it tracks the sun more accurately.

6. Contribution of solar cookers in mitigation potential of carbon dioxide

Many scientific studies reveals that overall CO_2 levels have increased 31% in the past 200 years, 20 Gt of Carbon added to the environment since 1800 only due to deforestation and the concentration of methane gas, which is responsible for ozone layer depletion has more than doubled since then. The global mean surface temperature has increased by 0.4–0.8 °C in the last century above the baseline of 14 °C [135]. The promotion of renewable and clean technology to produce energy is becoming a necessity to reduce greenhouse-gas emissions [136–142].

Panwar et al. [11], underlined in their review that, over the period from 1971 to 1995, as indicated by Table 4, CO_2 emissions grew at an average rate of 1.7% per year [143]. The outlook projects a faster growth rate of CO_2 emissions for the period to 2020, at 2.2% per year. By 2020, the developing countries could account for half of global CO_2 emissions.

Solar cooking technology may be one of the attractive options in developing countries capable to meet energy cooking demand with minimizing the CO_2 emission all over the world. Nandwani [144] conducted a study on the ecological benefits of solar cookers in Costa Rica and in the world as a whole, and then compared the advantages and limitations of solar ovens with conventional firewood and electric stoves. The payback period of a common hot box typed solar oven, even if used 6–8 months a year, is around 12–14 months; roughly 16.8 million tons of firewood can be saved and the emission of 38.4 million tons of CO_2 per annum can also be prevented according to the results. Hernandez and Huelsz [24] presented the optimization of optogeometrical design of a solar oven for the intertropical zone. The cooking test demonstrated that the oven prototype, which needs only four simple movements throughout the year, is suitable to cook three basic Mexican meals.

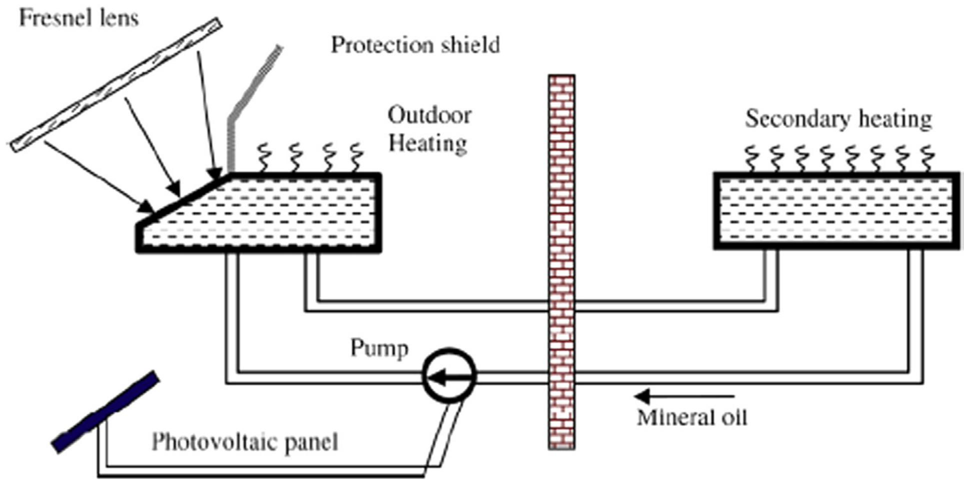

Fig. 25. Schematic view of solar thermal loop for the solar stove based Fresnel lens realized and tested by Valmiki et al. [132].

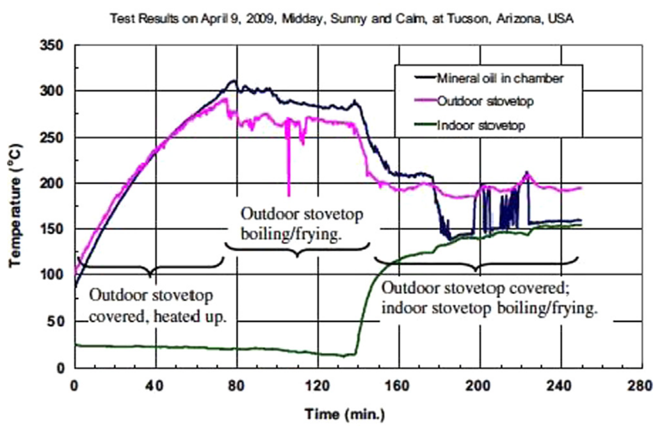

Fig. 26. Test results of temperature variation for the solar stove in operation, on April 9th, 2009, at Tucson, Arizona, USA [132].

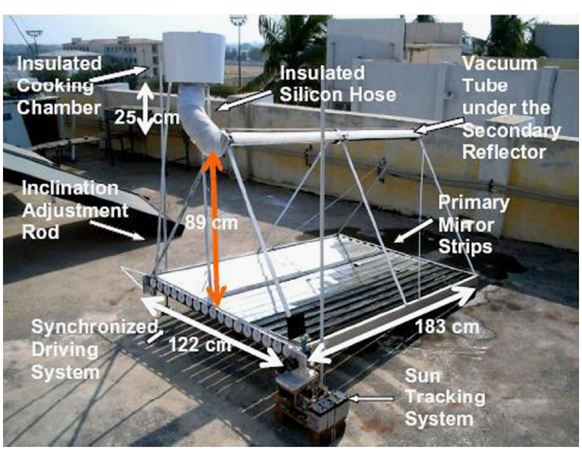

Fig. 27. Complete single vacuum tube based solar cooker realized by Farooqui [133].

It was estimated that the constructed oven can save a potential quantity of wood of 850 kg per annum.

Further, studies were conducted by Nahar for several years [145–147] on different designs of solar cookers in Indian climatic conditions and CO_2 emission potential. It was estimated that the payback periods varied between 1.28 and 4.82 years depending upon the cooking fuel replaces. For different cookers, the saved energy was also estimated maximum of 5175 MJ of energy per year. The use of the non-tracking solar cooker would result in a reduced release of CO_2 to the environment. Renewable energy resources will play an important role in the world's future [11]; the development of solar cooker systems will permit to meet the cooking energy demands and to resolve some serious problems related to traditional cooking, especially in developing countries.

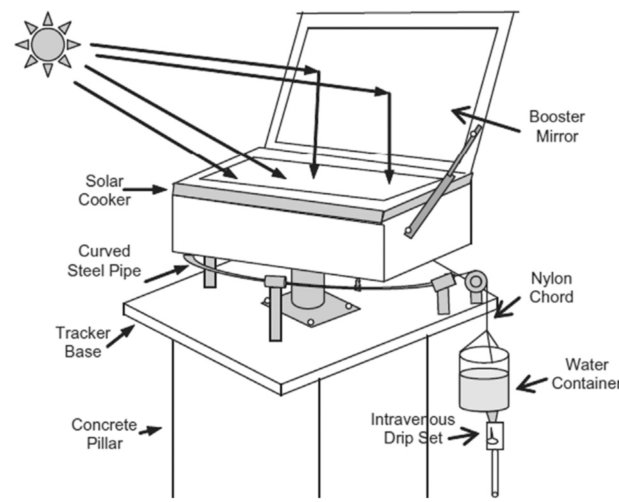

Fig. 28. The complete gravity based sun tracking system for box-type solar cooker [134].

Table 4
CO_2 emission by region (million tons of CO_2) [143].

	1971	1995	2010	2020
OECD	9031	10.763	13.427	14.476
Transition economic	3029	3135	3852	4465
China	875	3051	5322	7081
Rest of the world	1436	4791	8034	11.163
World	14.732	22.150	31.189	37.848

7. Conclusion

The present study explored recent advances in solar cooking technology were performed. Based on research conducted worldwide, various solar cooker type realizations and their thermal performance, and energetic and exergetic analysis are presented. This comprehensive review, suggested that cooking vessel, absorber plates should be

black painted for better thermal performance. Double glazing is also recommended to reduce heat losses.

The Solar cooking technologies can play a key role to reduce or substitute energy consumption from other sources in the near future. Effectively, solar cooking is a best option which offers a promising appliance for solar energy. In addition to its several advantages (i.e., fuel economy, CO_2 reduction, firewood conservation, and electricity saver, etc.), the large-scale diffusion of solar cookers is still limited because of diverse problems. To overcome this limitation and to apprehend more benefits of these systems, more research attempts must be done in future all over the world, to increase their efficiency and enhance their current performance.

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